Special Report 89-37

December 1989

U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Accuracy and precision of GOES data collection platforms for temperature measurements

Steven F. Daly, Charles H. Clark and Timothy Pangburn

RIM
RIVER ICE MANAGEMENT

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188
Exp. Date: Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION Unclassified	1B. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Special Report 89-37	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION U.S. Army Cold Regions Research and Engineering Laboratory 6b. OFFICE SYMBOL (if applicable) CECRL	7a. NAME OF MONITORING ORGANIZATION Office of the Chief of Engineers
6c. ADDRESS (City, State, and ZIP Code) Hanover, N.H. 03755-1290	7b. ADDRESS (City, State, and ZIP Code) Washington, D.C. 20314
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER River Ice Management Program CWIS 32227, CWIS 32228
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO / WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)

Accuracy and Precision of GOES Data Collection Platforms for Temperature Measurements

12. PERSONAL AUTHOR(S)

Daly, Steven F.; Clark, Charles H. and Pangburn, Timothy

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
	FROM ______ TO ______	December 1989	17

16. SUPPLEMENTARY NOTATION

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Data Collection Platforms — Hydrometeorological data
GOES — Remote sensing

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report describes an analysis of the accuracy and precision of data transmitted by 12 Data Collection Platforms (DCPs) over a one-month period. The DCPs were installed on the Monogahela, Ohio and Illinois rivers. A reference resistor with a known and stable resistance was installed at each DCP site. Comparison of the resistance calculated from the transmitted information with the actual resistance of the reference resistor allowed the accuracy and precision of the measurements made by the DCP to be determined. Four brands of DCPs were included in the test; two had 8-bit resolution and two had 12-bit resolution. The results were analyzed with respect to the nominal accuracy provided by the manufacturer and the expected analog-to-digital quantizing error. This error explained most of the imprecision of the 8-bit DCPs but only part of the imprecision of the 12-bit DCPs. A large bias for some of the results was apparently caused by an impedance mismatch. A means for correcting the data based on the reference resistor measurement is proposed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Steven F. Daly	22b. TELEPHONE (Include Area Code) 603-646-4100 / 22c. OFFICE SYMBOL CECRL-EI

PREFACE

This report was prepared by Steven F. Daly, Research Hydraulic Engineer; Charles Clark, Electronics Technician, both of the Ice Engineering Research Branch; and Timothy Pangburn, Research Hydraulic Engineer, Geological Sciences Branch, U.S. Army Cold Regions Research and Engineering Laboratory. The work was funded by the Office of the Chief of Engineers, Directorate of Civil Works, under the River Ice Management (RIM) program, CWIS 32227, *Forecasting Ice Conditions on Inland Waters*, and CWIS 32228, *Remote Ice Monitoring System*.

The report was technically reviewed by Dr. James Lever and Dr. Steven Arcone of CRREL. The authors appreciate the assistance of Francis E. Doyle, Hydrologic Technician, U.S. Army Engineer District, Pittsburgh, whose insight and understanding of the GOES Data Collection Platforms and their installation, gained through long experience, was generously shared with the authors. The authors also thank the following CRREL personnel: Clay Thompson for performing the statistical analysis of the data and contributing to an early draft of the report; Edward Perkins and his staff for preparing the figures; and David Cate for his editorial work.

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.

CONTENTS

Page

Abstract ii
Preface iii
Introduction 1
Equipment 1
  DCP network 1
  Data collection platforms 1
  Temperature measurement 3
Data 4
Discussion 5
  Handar DCP 7
  LaBarge DCP 7
  Sutron DCP 7
  Synergetics 8
Analysis of bias 8
Summary 8
Appendix A: Histograms of reference resistor measurements 11

ILLUSTRATIONS

Figure
  1. Locations of the DCP installations 2
  2. Interface schematic diagram. 4
  3. Six-month records for three sites 5

TABLES

Table
  1. DCP specifications 3
  2. Results of reference resistor measurements 3
  3. DCP statistics 5

Accuracy and Precision of GOES Data Collection Platforms for Temperature Measurements

STEVEN F. DALY, CHARLES H. CLARK AND TIMOTHY PANGBURN

INTRODUCTION

The use of Data Collection Platforms (DCPs) for transmitting hydrometeorological data to Geostationary Operational Environmental Satellites (GOES) is becoming increasingly widespread as the need for this real-time information increases. This information is needed to monitor flood levels, precipitation rates, water temperatures, and other variables. A recent use of DCPs has been to measure and transmit air and river water temperatures as part of an ice forecasting system developed for navigable inland waterways. Water and air temperature measurements provide important initial and boundary conditions, and these data must be as accurate as possible.

This report describes an analysis of the accuracy and precision of data transmitted by 12 DCPs over a one-month period. The data transmitted were voltages measured by the DCPs. The voltages are directly related to the electrical resistance of the thermistors used to measure air and water temperature. After these transmitted data are received, resistance values are calculated from the voltages, and temperatures are determined from the resistances. At each site, one thermistor was replaced with a "reference" resistor that had a known and stable resistance. Comparison of the resistance calculated from the transmitted voltages with the actual resistance of the reference resistor allowed us to determine the accuracy and precision of the measurements made by the DCP. Measuring the resistance of a reference resistor is an appropriate test of DCP performance because the resistance of thermistors is calculated using an identical procedure. The stability of these measurements over a six-month period at selected sites is also described here. Based on the reference resistor measurements, a means of correcting the measured thermistor values to eliminate bias is proposed.

EQUIPMENT

DCP Network

GOES DCPs are used throughout the Corps of Engineers to collect and transmit hydrometeorological data. The DCPs discussed in this report were installed at twelve sites on the Monongahela, Ohio and Illinois rivers (Fig. 1). All sites have thermistors to measure air and water temperature. Most sites also have sensors to measure relative humidity, solar radiation, barometric pressure, wind speed and direction, precipitation and river stage. Every site has 110-V commercial power available. The DCPs sample and record data every hour on the hour, and they transmit every four hours. All data are sent through the GOES system. In this case, data were received at a downlink located at the Ohio River Division of the Corps of Engineers in Cincinnati, Ohio.

Data collection platforms

Twelve DCPs were used in the analysis: seven were manufactured by Sutron, two by Synergetics, one by Handar and two by LaBarge. Table 1 lists the relevant specifications of each brand. The locations where each type was installed are listed in Table 2.

In operation, the DCPs are all essentially similar except in their ability to apply a gain to the measured voltages and in the resolution of the analog-to-digital (A/D) processor. The first step of the operation is to apply a gain to the measured voltage; only the Sutron and Synergetics DCPs have this ability. Errors introduced at this point result from nonlinear gains, zero offsets and the "internal noise" of the processor. The next step on the DCP operation is to convert the measured voltage to a digital number. The accuracy and precision of this step is limited by the resolution of the A/D processor. The DCPs discussed in this report have either 8-bit resolution (1 part in 256, as in the Han-

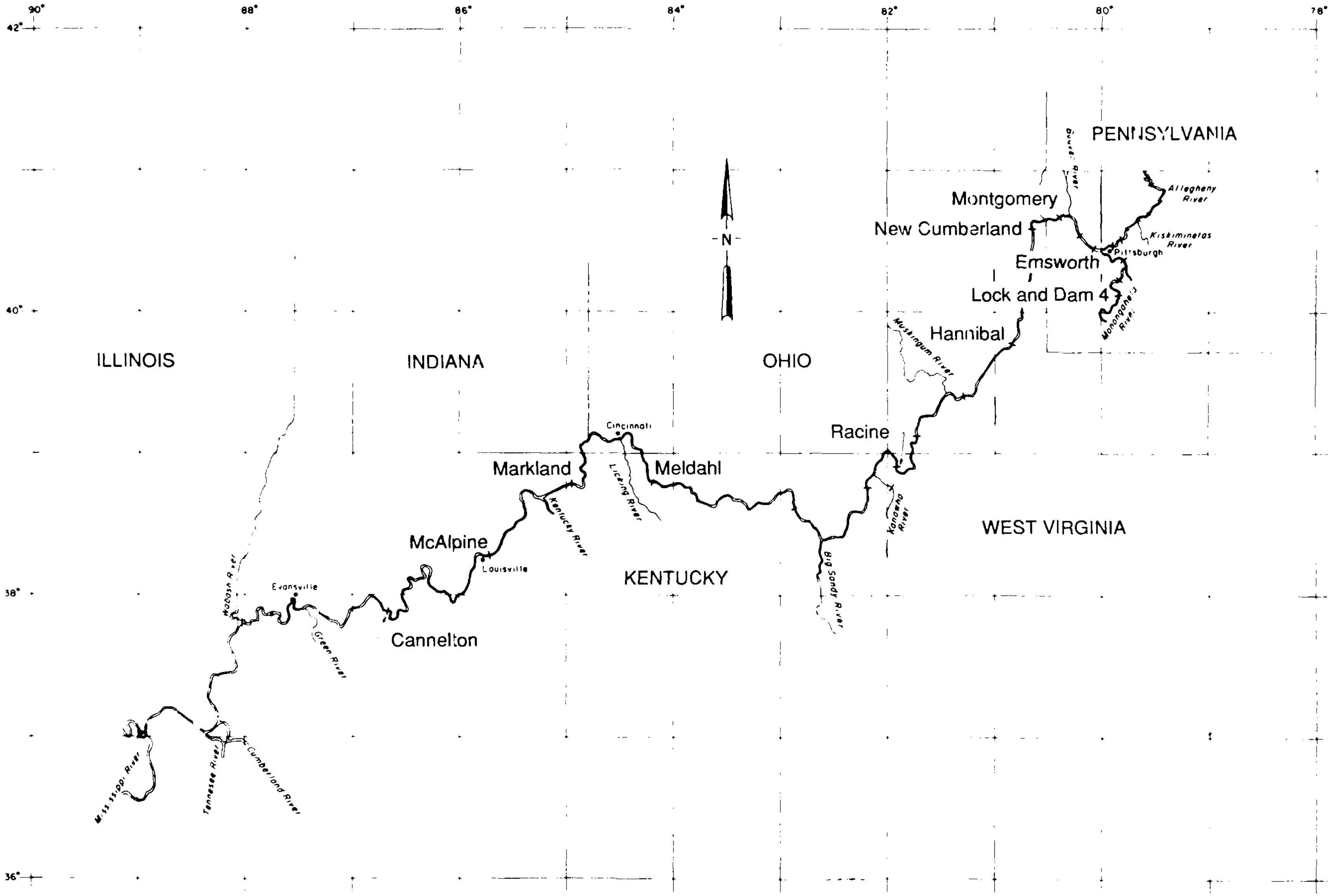


Figure 1. Locations of the DCP installations. The Peoria and Starved Rock sites are not shown; they are on the Illinois River.

Table 1. DCP specifications.

Brand	*Model*	*Nominal accuracy (full scale)*	*Resolution (bits)*	*Range (V)*	V_o *(V)*
Handar	560A	0.4%	8	0–5	4.7
LaBarge	DCP1286	LSB	8	0–5	4.7
Sutron	8004D	0.05%	12	0–1	0.6
Synergetics	3400 (with 3452A Interface)	0.1%	12	0–1	0.6

Table 2. Results of reference resistor measurements.

DCP type	*Site*	*Number of readings*	*Resistance (ohms)* *Mean*	*Std. dev.*	*Min.*	*Max.*	*Bias*	*CLLSB (%)**
Handar	McAlpine Locks	745	10,089	72.9	9,995	10,219	+89	92
LaBarge	Markland Locks & Dam	725	9,988	78.6	9,791	10,213	-22	88
	Cannelton Locks & Dam	742	9,974	75.4	9,792	10,106	-26	90
Sutron	Lock & Dam 4	745	10,428	20.5	10,372	10,498	+428	45
	Emsworth Locks & Dam	741	10,436	18.2	10,380	10,490	+436	50
	Montgomery Locks & Dam	471	10,482	14.4	10,438	10,528	+482	60
	New Cumberland Locks & Dam	741	10,545	20.0	10,399	10,599	+545	45
	Hannibal Locks & Dam	693	10,409	24.1	10,343	10,493	+409	38
	Peoria Lock & Dam	714	10,844	16.1	10,801	10,884	+844	54
	Starved Rock Lock & Dam	735	10,569	27.6	10,480	10,664	+569	34
Synergetics	Racine Locks & Dam	741	9,974	33.8	9,800	10,090	-26	28
	Meldahl Locks & Dam	698	9,928	187.9	9,430	10,460	-72	†

* Confidence limit of the least significant bit.
† DCP not operating properly.

dar and LaBarge DCPs) or 12-bit resolution (1 part in 4096, as in the Sutron and Synergetics DCPs). Additionally, errors may be introduced by the "internal noise" of the A/D processor. Finally, the digital result is coded onto the carrier signal and transmitted to the GOES system. The error that results from each step in the DCP operation determines the overall performance and the nominal accuracy of the DCP. Generally, the nominal accuracy is provided by the manufacturers (Table 1).

Temperature measurement

The method for measuring water and air temperature uses thermistors, small electronic components made of semiconductor material whose electrical resistance is determined by its temperature. The properties of the thermistor can be controlled so that small changes in temperature produce relatively large changes in resistance. The relationship of the thermistor resistance and temperature is highly nonlinear but well known, and

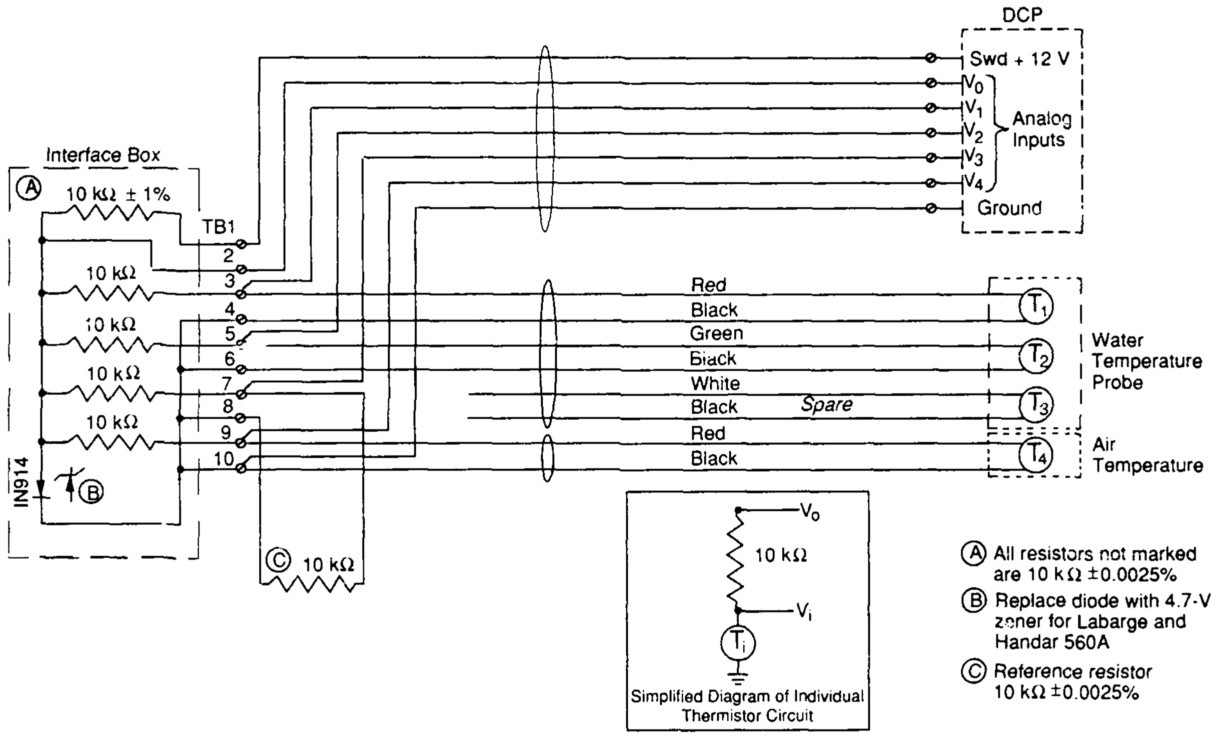


Figure 2. Interface schematic diagram.

the exact response of thermistors can be determined through calibration. As DCPs measure only voltages, a voltage divider circuit is necessary to serve as an interface between the thermistors and the DCP (Fig. 2). The nominal switched 12-V D.C. available from the DCP is used to power the voltage divider circuitry. This voltage is first passed through a 10,000-ohm resistor to supply approximately 1.2 mA to a diode. The diode is conducting, and the voltage difference across its junction is the excitation voltage applied to the thermistor circuit V_0. Each thermistor circuit consists of a "dropping" resistor and a thermistor in series. The dropping resistor is a precision, wire-wound 10,000-ohm resistor with a nominal accuracy of 0.0025% and a resistance stability of 0.0005% at –55°C to 12.5°C. The voltages measured by the DCP are the excitation voltage V_0 and the voltage across each thermistor V_t. The thermistor resistance R_t is calculated by

$$R_t = R_0\left[\frac{V_t}{V_0 - V_t}\right] \qquad (1)$$

where R_0 is the resistance of the dropping resistor. The resistance of the thermistor is then entered into the Steinhart–Hart equation, from which the thermistor temperature is calculated. The reference resistors used at all of the sites were identical to the dropping resistors described above. Reference resistors occupy the same position in the voltage divider circuit as a thermistor, and the resistance of the reference resistor is calculated using eq 1.

DATA

The reference resistor measurements analyzed were based on the transmitted voltages collected hourly between 1 January and 31 January 1988. All the sites except Montgomery Locks and Dam (L & D) recorded between 600 and 745 voltage measurements for that month, the difference in number being caused by problems in transmission or reception. The DCP at Montgomery L & D did not transmit for about two weeks. The mean, standard deviation, maximum and minimum of the calculated reference resistor resistances for each site are listed in Table 2.

Histograms of the reference resistor values were plotted for each site and combined for each DCP type (Appendix A). The combined statistics for each DCP type are listed in Table 3.

Figure 3 displays the calculated reference resis-

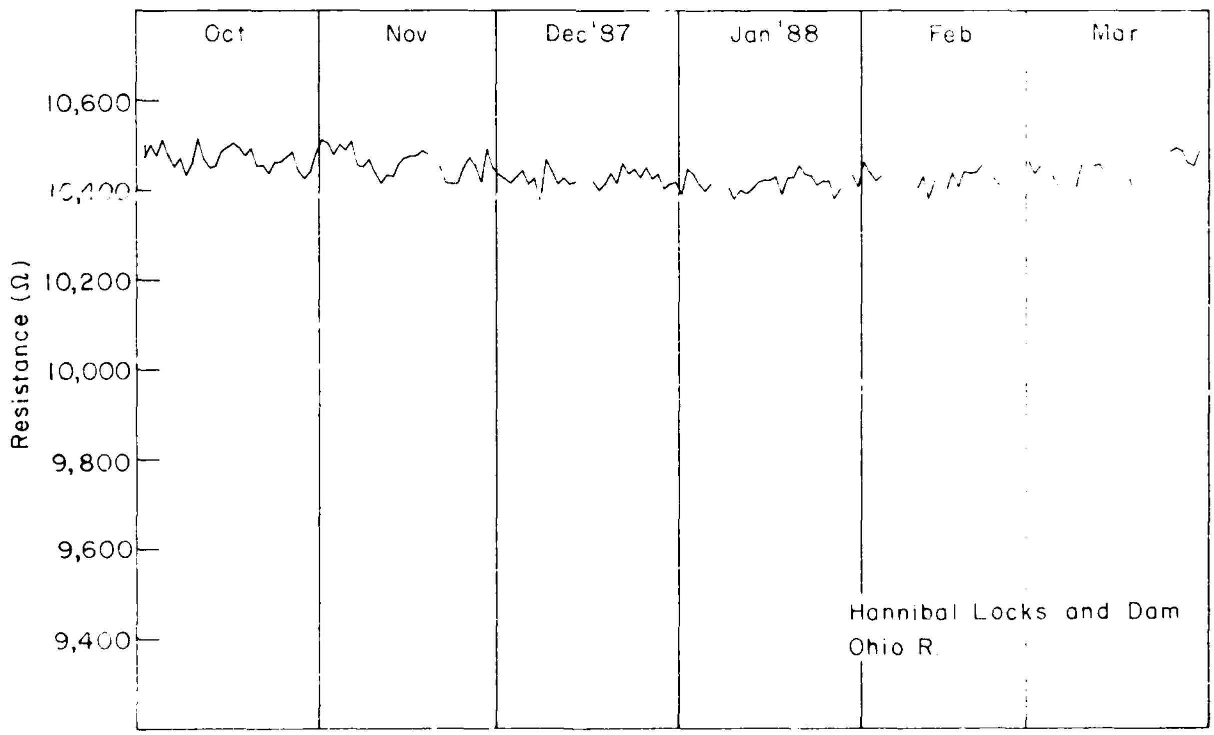
Table 3. DCP statistics.

DCP type	Number of readings	Resistance (ohms) Mean	Median	Std. dev.	Min.	Max.
Handar	745	10,089		72.9	9,995	10,219
LaBarge	1,466	9,981	10,000	85.4	9,792	10,213
Sutron	4,840	10,532	10,483	143.1	10,343	10,884
Synergetics	1,439	9,952	9,970	135.0	9,430	10,450

tor resistance over a six-month period from Hannibal L & D (Sutron DCP), Racine L & D (Synergetics DCP), and Markland L & D (LaBarge DCP). The six-month period started on 1 October 1987 and ended on 31 March 1988. The results for these three sites do not show any consistent trends and are fairly constant over this time period.

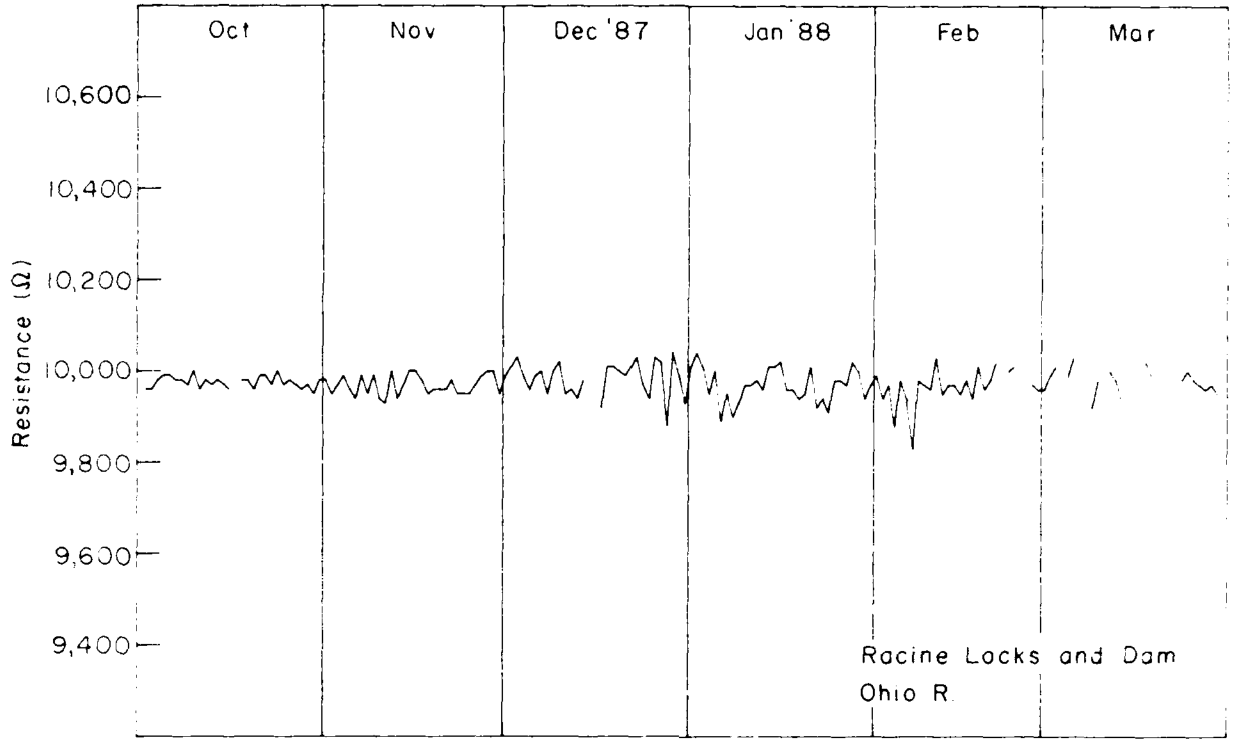
DISCUSSION

It is appropriate at this point to define some terms that we have been using. *Accuracy* describes the deviation of the measured values from the known values and is indicated by the difference between the mean of the measured values and the known value. The *bias* of the measurements is the amount that the mean of the measurements and the known value differ; it is used interchangeably with accuracy. *Precision* indicates the ability to reproduce a given reading with a given accuracy. The precision is indicated by the spread of the measurements about the mean; the standard deviation of the measurements is a good measure of the precision. The smaller the standard deviation about the mean measurement, the more precise the measurements are. The *nominal accuracy* of the DCP is an accuracy value supplied by the manu-

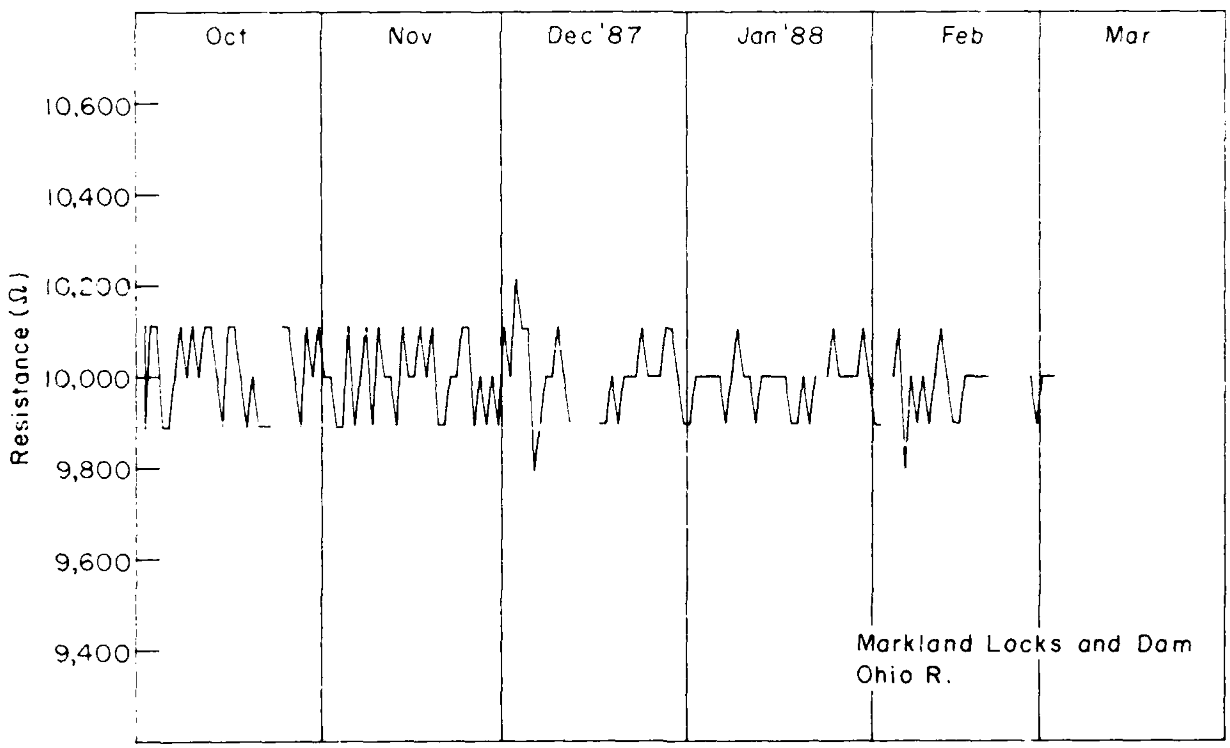


a. Hannibal Locks and Dam (Sutron DCP).

Figure 3. Six-month records for three sites.



b. Racine Locks and Dam (Synergetics DCP).



c. Markland Locks and Dam (LaBarge DCP).

Figure 3 (cont'd). Six-month records for three sites.

facturer. It results from the cumulative error of each step in the DCP operation.

It is of interest to determine if the results of our measurements can be explained by the nominal accuracy of the DCP. It is also of interest to assess the degree to which the imprecision can be explained by the analog-to-digital quantizing error. This error is a fundamental limit to precision that is determined solely by the resolution of the analog-to-digital processes, that is, the number of bits used. The quantizing error is ±$^1/_2$ LSB (least significant bit). If we assume that the measurement results can be approximated by a normal distribution, then the confidence limits of the normal distribution that are associated with ±$^1/_2$ LSB will be a good indication of the degree to which the results can be explained by the quantizing error.

Handar DCP

There was only one Handar DCP included in this study. It had a resolution of 8 bits, it did not have the ability to apply a gain to the measured voltage, and it had only one voltage measurement range of 0–5 V. The nominal accuracy is ±0.4% of the full-scale reading, or ±20 mV. The results of the measurements to be expected, given the nominal accuracy of the DCP, can be determined from eq 1 as follows: V_o is expected to be the nominal excitation voltage supplied by the Zener diode, and the voltage across the reference resistance V_r is assumed to be exactly half of the excitation voltage. These nominal voltages are then varied by ±20 mV. The resultant range is 9,749–10,260 ohms. The maximum and minimum results are within this range (Table 2). This implies that the accuracy of the measurements is within the nominal accuracy of the DCP. Next we can look at the quantizing error. The resolution of the Handar is 8 bits, or 1 part in 256. Applied over 5 V this is a resolution of 19.53 mV per bit, and the potential quantizing error is ±$^1/_2$ LSB, or ±9.77 mV. If we again use the nominal voltages for V_o and V_r, the range of imprecision associated with the quantizing error from eq 1 is ±125 ohms. The confidence limit associated with the quantizing error (CLLSB) is 92%, implying that the quantizing error explains a large part of the imprecision of the Handar.

LaBarge DCP

There were two LaBarge DCPs included in this study. They had a resolution of 8 bits, they did not have the ability to apply a gain to the measured voltage, and they had one voltage measurement range of 0–5 V. While the nominal accuracy of the LaBarge is not directly stated in the literature supplied, a nominal accuracy of ±1 LSB can be inferred from the description of the equipment and its operation. Following the procedure described for the Handar, we can see that this translates to ±19.53 mV, and we would expect the same results as above. The maximum and minimum results are within this range (Table 2), implying that the accuracy of the measurements is within the nominal accuracy of the DCP. The quantizing error of the LaBarge is identical to the Handar (±9.77 mV, or ±125 ohms). The confidence limit associated with the quantizing error are 88% and 90%, implying that, similar to the Handar, the quantizing error explains a large part of the imprecision of the LaBarge DCPs.

Sutron DCP

Sutron is represented at seven sites in this study. The Sutron DCPs had a resolution of 12 bits, and a gain could be applied to the measured voltage. A range of 0–1 V was used at all sites. The nominal accuracy is stated as ±0.05%, and we assume that this applies to the full scale, although this is not clear in the published specifications. This nominal accuracy would translate to an uncertainty of ±0.5 mV. If the nominal excitation voltage supplied by the silicon diode (0.6 V) is assumed and the voltage across the reference resistor is assumed to be exactly half of the excitation voltage, the results of the measurements to be expected given the nominal accuracy of the DCP can be determined from eq 1 by varying the nominal voltage by ±0.5 mV. This range is 9,950–10,050 ohms. All the Sutron measurements fall far outside this range (Table 2). All Sutron results show a large, unexpected bias. The reason for this bias and the means to correct for it are discussed in the next section.

Neglecting this bias for the moment, we see that the imprecision of the measurement about the mean as indicated by the standard deviation is relatively small, only about one third that of the Handar or LaBarge DCPs. The resolution of the Sutron is 12 bits, or 1 part in 4096. Applied over 1 V this is a resolution of 0.24 mV per bit and a potential quantizing error of ±0.12 mV. If we again assume the nominal voltages as above, the range of imprecision associated with the quantizing error from eq 1 is ±12 ohms. The confidence limit associated with this quantizing error (CLLSB) ranges from 28% to 60% for the Sutron sites. Therefore, we see that a part, but by no means all, of the imprecision of the Sutron measurements can be explained by the quantizing error. The remainder of the impre-

cision may be caused by the application of the gain to the measured voltage. This process can introduce zero offsets and nonlinearities into the measured voltage. The application of gain may also account for the more normal appearance of the individual Sutron histograms.

Synergetics

There were two Synergetics DCPs included in this study. They had a resolution of 12 bits, and they had the ability to apply a gain to the measured voltage. The voltage range 0–1 V was used at both sites. The nominal accuracy is stated as 0.1% of the full scale (maximum) and 0.025% of the full scale (typical), although the meaning of "typical" is not made clear. This nominal accuracy would translate to an uncertainty of 1 mV maximum and 0.25 mV typical (to use the manufacturer's nomenclature). The range of measurements associated with this accuracy would be 9,900–10,100 ohms (maximum) and 9,950–10,050 ohms (typical). The maximum and minimum measurements fall outside these ranges (Table 2), although the means are within the maximum specified ranges. The biases are not as large as with the Sutron DCPs. The two Synergetics DCPs differ widely in their performance. This can especially be seen in the imprecision of the measurements. The quantizing error is the same as the Sutron (12 ohms). The confidence limits associated with this quantizing error is 28% at Racine Lock and Dam and negligible at Meldahl Lock and Dam. The result at Meldahl Lock and Dam indicates that the internal noise of the DCP is relatively large. In fact, this procedure may provide an automated means of detecting DCPs that are not functioning correctly.

ANALYSIS OF BIAS

Measurements in the laboratory showed that the large biases in the Sutron DCP data result from a leakage current. The leakage current is associated with the impedance mismatch between our voltage divider circuit and the DCP. The voltage divider circuit shown in Figure 2 can be reanalyzed assuming the presence of a leakage current. The measured voltage drop V_t across R_t is then

$$V_t = (I + I_{os})R_t \qquad (2)$$

where I is the circuit current and I_{os} is the offset leakage current. The relative voltage measurement bias B can then be found from

$$B = (V_t - V_A)/V_A = (I_{os}/V_o)\,(10{,}000 + R_t) \qquad (3)$$

where V_A is the "true" voltage drop without the leakage current. The relative voltage bias will be reduced if I_{os} is reduced, the excitation voltage V_o is increased, or the total resistance of the divider circuit is reduced. The bias of the reference resistor resistance calculation can be determined as

$$(R_t - R_f)/R_f = B/(1-B) \qquad (4)$$

where R_f is the true resistance of the reference resistor. The bias of the reference resistor calculation will be reduced if the value of B is made very small, as above. Replacing the silicon diode with a Zener diode for the 8-bit DCPs, as described above, increased the applied excitation voltage, which had the effect of reducing B, in this case, by an order of magnitude. It is not clear whether this can be seen in the results for the 8-bit DCPs, where the bias introduced would be less than the resolution of the measurement.

Given the existence of this leakage current, the transmitted measurements can be corrected by including a reference resistor in each interface. The resistance of each thermistor can be calculated (assuming the same offset current on each channel) by the formula

$$R_t = (10{,}000)(V_t)/(2V_r - V_t) \qquad (5)$$

where R_t is the true resistance of the thermistor, V_t is the voltage measured across the thermistors, and V_r is the voltage measured across the reference resistor. The true thermistor resistance is then a function of the voltages across the thermistor and the reference resistor.

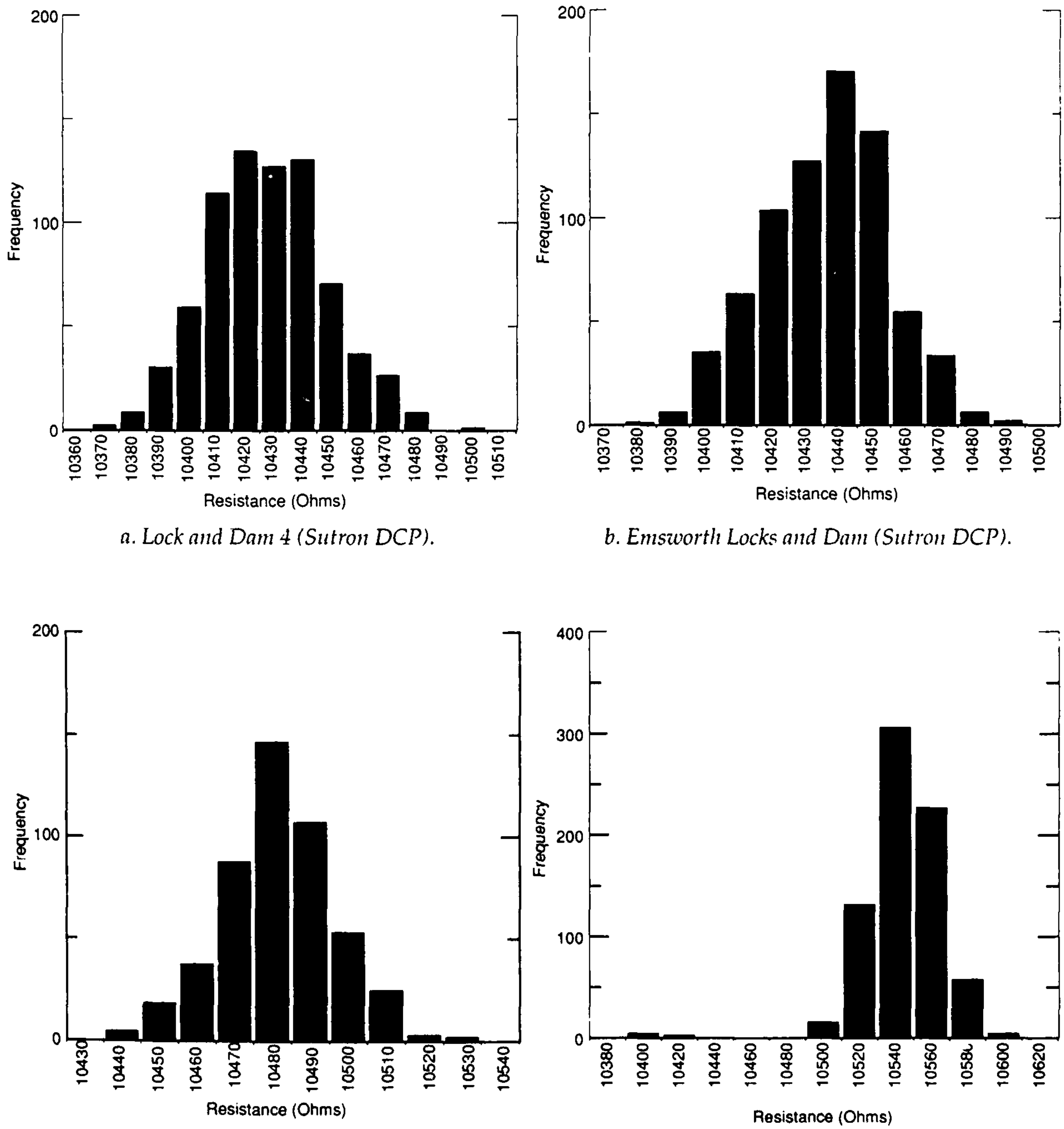
A possible hardware solution would be to include an operational amplifier in the voltage divider circuit. The operational amplifier with unity gain would reduce the apparent output impedance of the interface box so that the effect of the offset current would be negligible.

SUMMARY

The reference resistors provide a check on the DCP performance and a means to reduce the bias associated with offset leakage currents. These biases can be quite large for certain DCPs, as demonstrated by the recorded measurements. The existence of the bias was not anticipated but was uncovered through a rigorous program of field check-

ing of transmitted data. Once detected, the problem was corrected, with the major limitation that the offset current must be assumed to be the same on each channel of the DCP. Preliminary field checking indicates that this assumption is valid. Anticipating and correcting for the large biases introduced by the offset current would be easier if the manufacturers of DCPs would provide complete and up-to-date specifications for their equipment. This has not been the case, and although some information has been made available, researchers should not install DCPs for which full specifications are not available.

APPENDIX A. HISTOGRAMS OF REFERENCE RESISTOR MEASUREMENTS



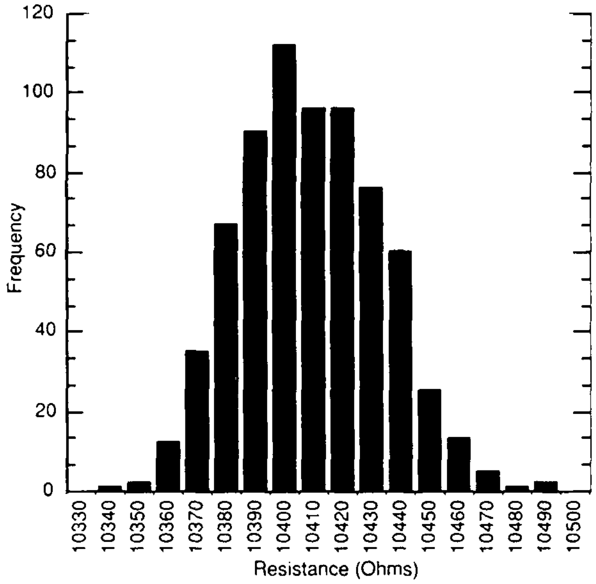
a. Lock and Dam 4 (Sutron DCP).

b. Emsworth Locks and Dam (Sutron DCP).

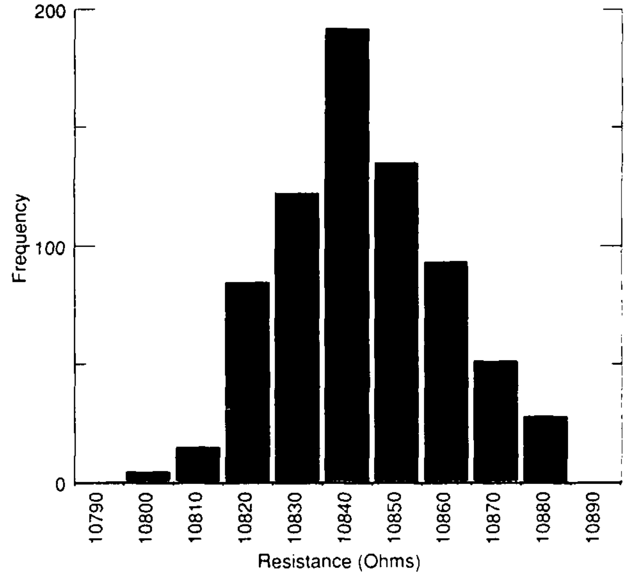
c. Montgomery Locks and Dam (Sutron DCP).

d. New Cumberland Locks and Dam (Sutron DCP).

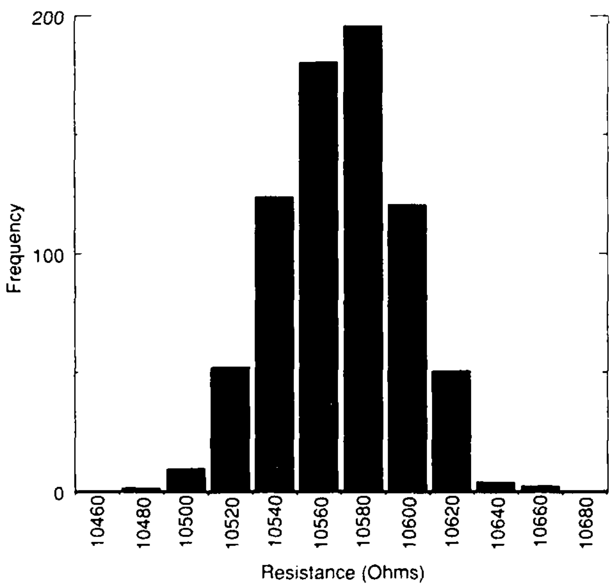
Figure A1. Measurements at each site.



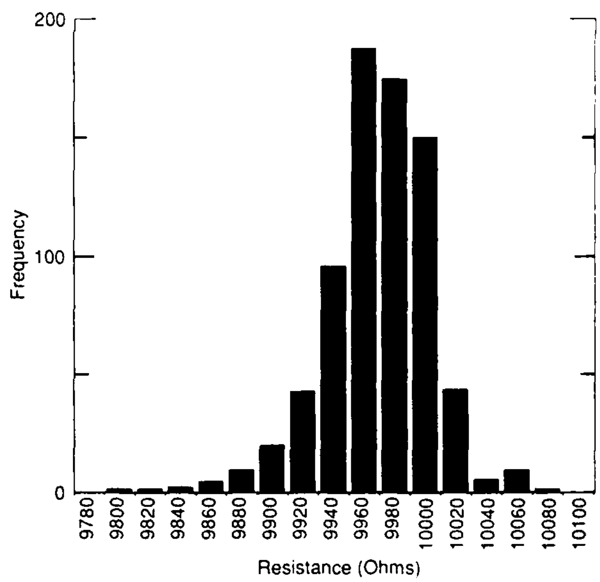
e. Hannibal Locks and Dam (Sutron DCP).



f. Peoria Lock and Dam (Sutron DCP).

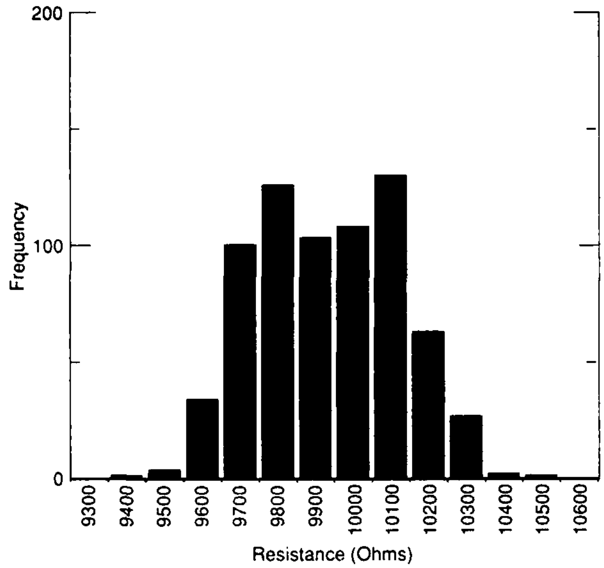


g. Starved Rocks Lock and Dam (Sutron DCP).

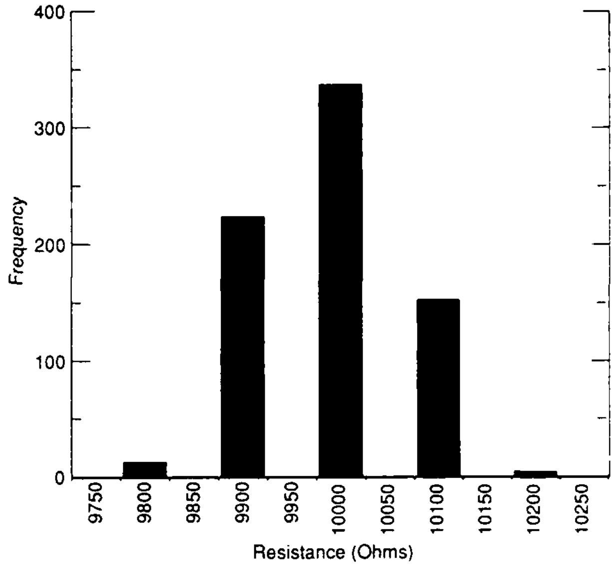


h. Racine Locks and Dam (Synergetics DCP)

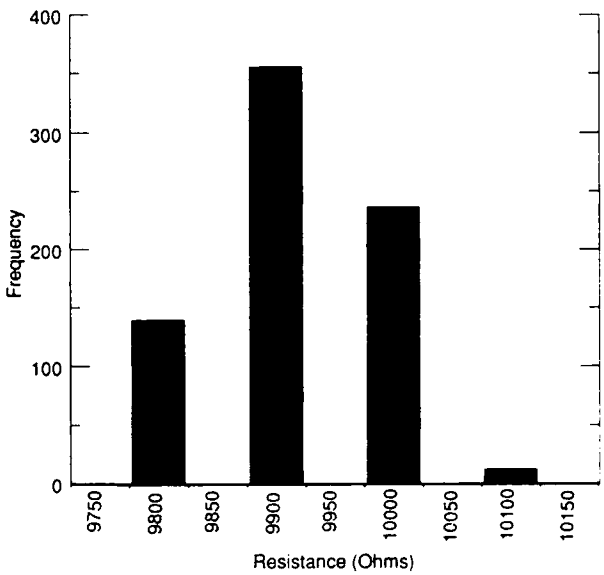
Figure A1 (cont'd). Measurements at each site.



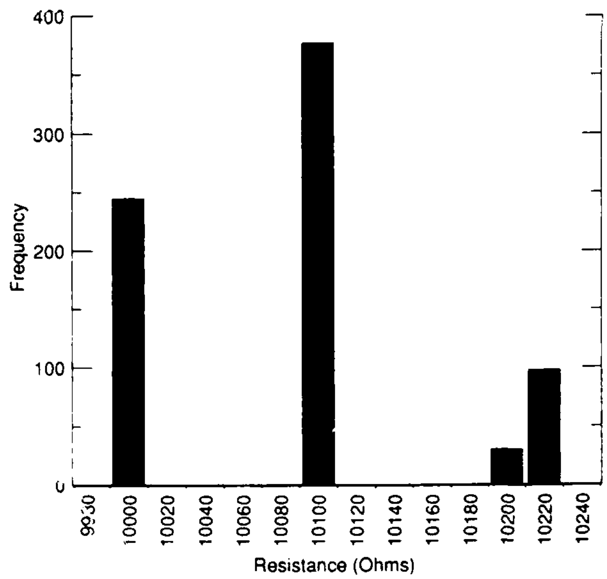
i. Meldahl Locks and Dam (Synergetics DCP).



j. Markland Locks and Dam (LaBarge DCP).

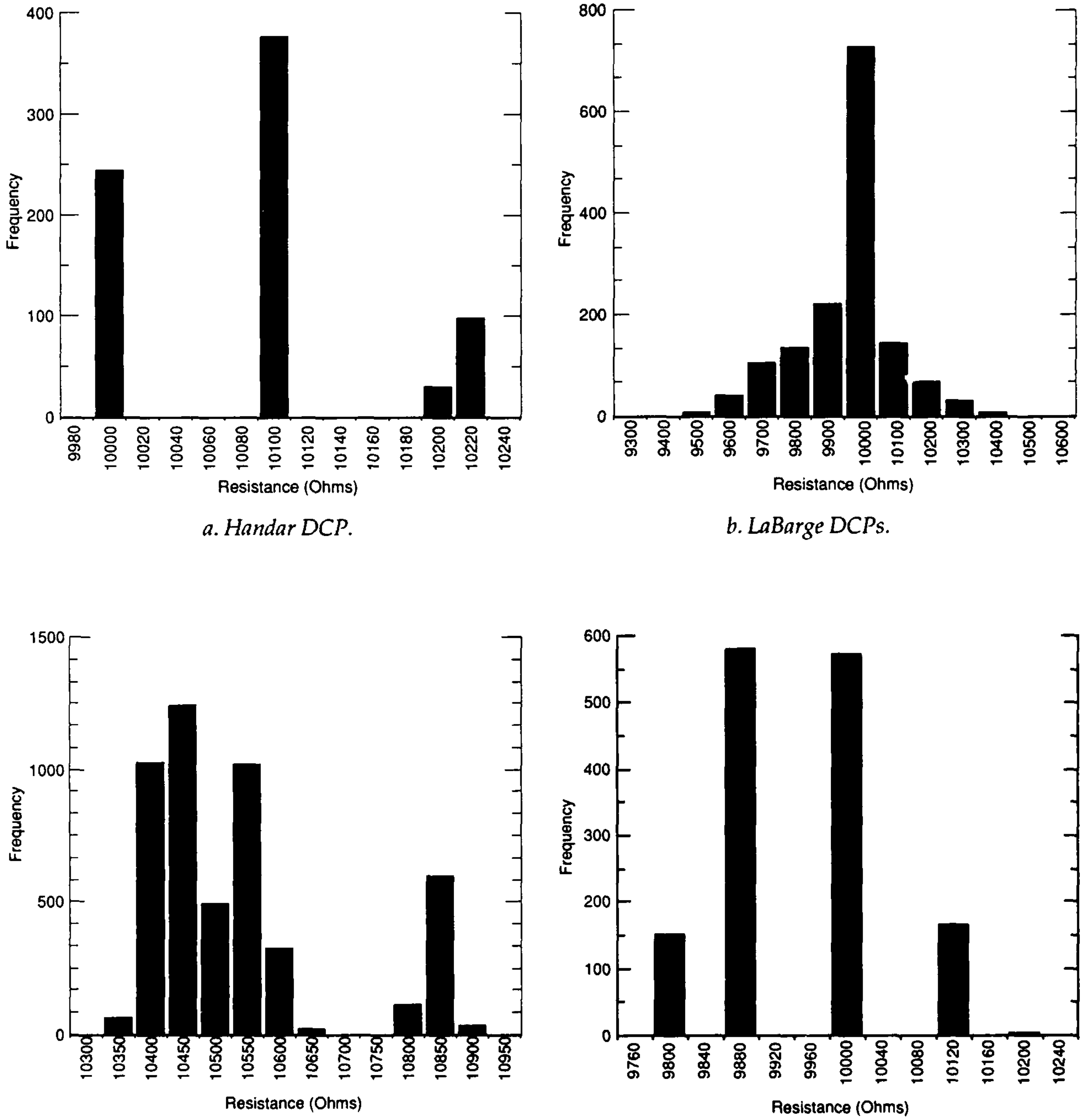


k. Cannelton Locks and Dam (LaBarge DCP).



l. McAlpine Locks and Dam (Handar DCP).

Figure A1 (cont'd).



a. Handar DCP.

b. LaBarge DCPs.

c. Sutron DCPs.

d. Synergetics DCPs.

Figure A2. Measurements for each DCP type.

☆ U.S.G.P.O.: 1990- 700-057/02070